

# EXTREME OPTICS AND IMAGING

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Proposers Day Briefing

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## HIGH LEVEL OVERVIEW

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# What is EXTREME about?

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Break away from traditional rules and “laws” that artificially constrain modern optics, and establish a fundamentally new design space for optical components, systems and architectures revolutionizing performance.



# EXTREME challenge

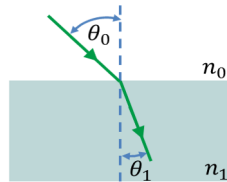


$$\begin{aligned}\nabla \cdot E &= \frac{\rho}{\epsilon} & \nabla \times E &= -\frac{\partial B}{\partial t} \\ \nabla \cdot B &= 0 & \nabla \times B &= \epsilon\mu \frac{\partial E}{\partial t} + \mu \cdot J\end{aligned}$$

## Natural Materials

### Leads To

- “Law” of reflection
- “Law” of refraction



Components

Design strategy

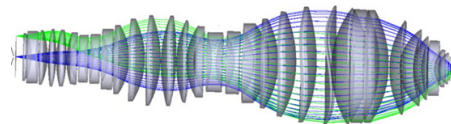
### Leads To

- Monofunctional
- Optical “work” confined to surfaces

Functionality

### Leads To

- Unsustainable complexity



Architectures

**Status: Classical Optics has been historically constrained by a set of assumptions, rules, “laws”, and practices which are considered pillars of optical design**



# EXTREME vision

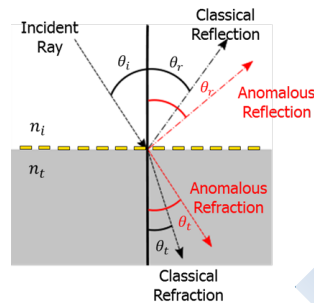


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## Engineered Materials

### Leads To

- Generalized laws of reflection and refraction for new architectures
- Functionality decoupled from geometry



### Leads To

- Multi-functional devices
- Optical “work” in volume, minimize SWaP
- Reconfigurability

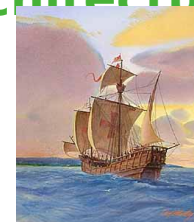
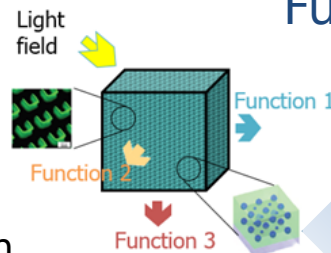
**Goal:** By introducing *engineered materials*, EXTREME would create a revolution in optics by enabling **new** components, functionality, and architectures unconstrained by artificial limitations

## Design strategy

New Components

New Functionality

New Architectures





# What will EXTREME accomplish?

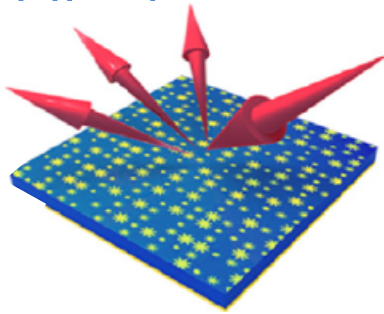
Optical System Categories	Today	EXTREME (objective)
<b>Components</b>	Bulk optics	Fully EnMat optical components
<b>Functionality</b>	Each component performs a single function / Functionality coupled to geometry	Single EnMat optic replaces many bulk components / Functionality decoupled from geometry
<b>Architectures</b>	Multiple components in series perform a single optical mapping	Fully EnMat system capable of arbitrary and reconfigurable optical mappings
<b>Modeling and Design</b>	Single-scale physics, Disjoint optimization	Rigorous and seamless modeling & optimization across all spatial scales

Engineered Materials (EnMats): Meta-materials, scattering structures, volume holograms.



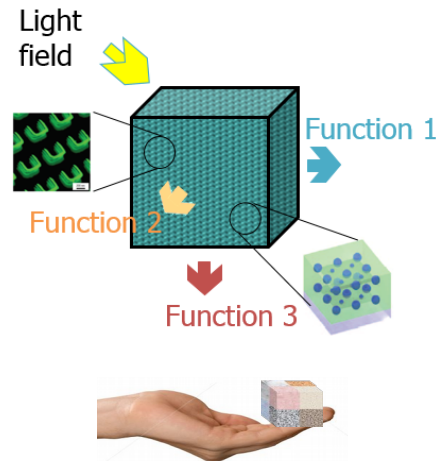
# How? Program components and challenges

EnMats can modify “laws” of geometrical optics and expand the space of optical architectures

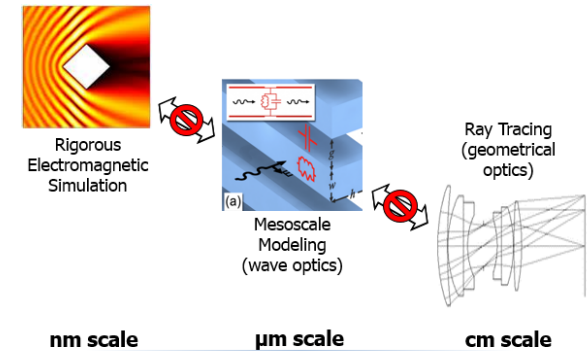


Light refracts/reflects into full 3D space

EnMats can enable multifunctional devices and new optical architectures



Multiscale modeling can enable design and optimization of EnMats across vastly different scales



## Challenges and opportunities:

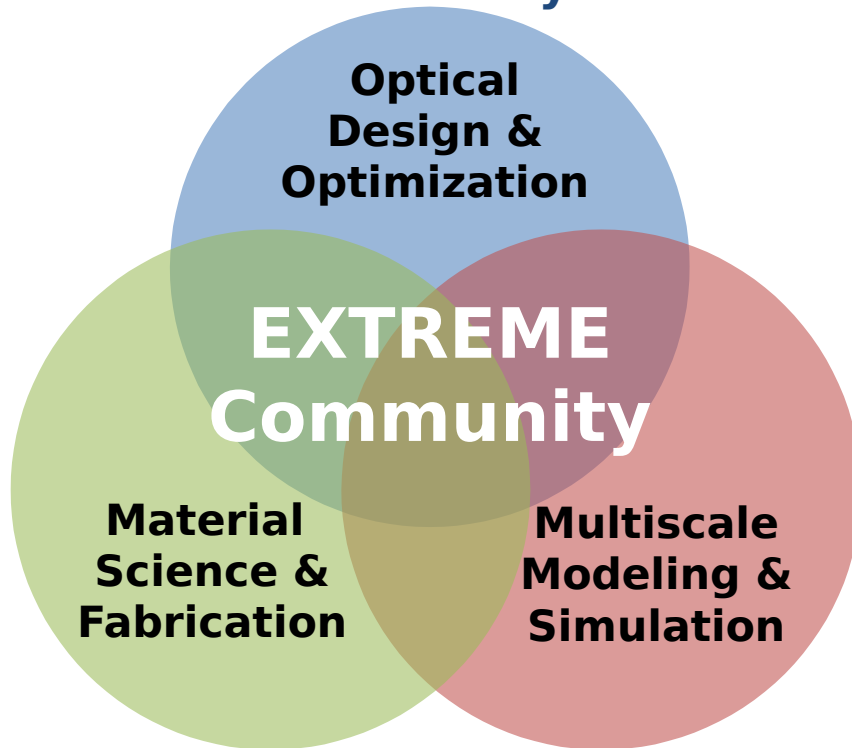
- Optical loss (may require internal gain) and bandwidth
- Very small size structures (scale up may be a problem)
- Unknown performance limits and parameter tradeoffs

- Inability to solve forward and inverse wave propagation across scales
- Information loss when transitioning between models and spatial scales



# EXTREME Program Structure

**EXTREME will cross-connect currently disparate communities of engineered materials, optical design, and multi-scale modeling and optimization to establish foundations for optics for the 21st century**



## Program Structure

TA1: Modifying the Principles of Conventional Optics

TA2: Multifunctional Optics

TA3: Modeling, Design, and Optimization

TA3(a): Multiscale Physics Based Modeling

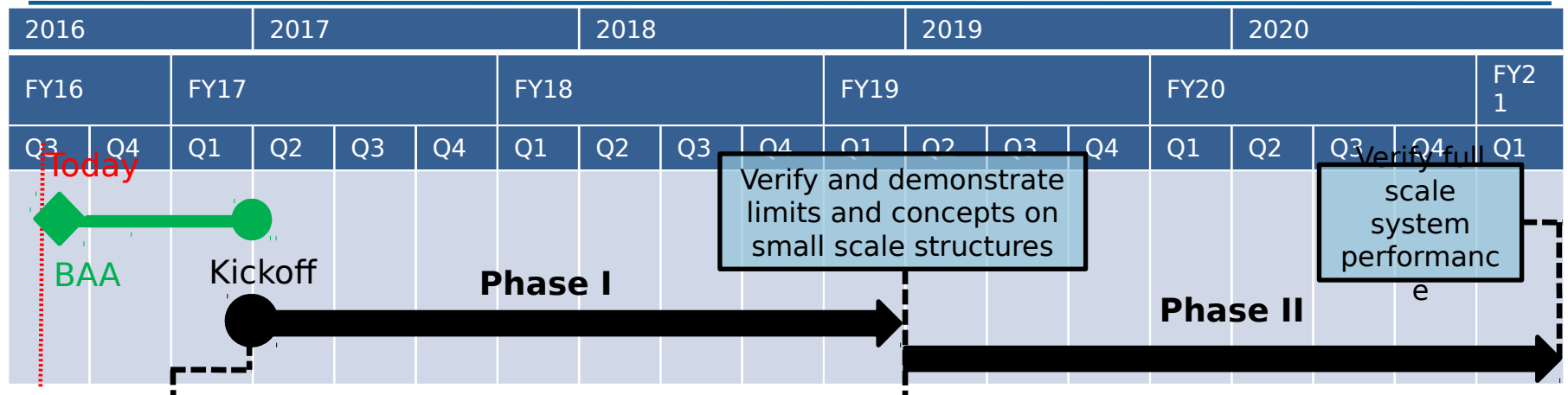
TA3(b): EnMat-based Optical Design and Optimization

**To focus integration of efforts, there will be a challenge problem that will be described in the detailed discussion of the BAA to follow**





# EXTREME Program Schedule



	Phase I: Exploration & Verification	Phase II: Design, Build & Demonstration
TA1: Modifying the Principles of Conventional Optics	<ul style="list-style-type: none"> <li>Analyze ultimate limits of EnMats to modify "laws" of light propagation</li> <li>Develop concepts to address current limitations of EnMats</li> <li>Propose system architectures utilizing conformal and non-conformal EnMats</li> </ul>	<ul style="list-style-type: none"> <li>Design and optimize system concepts from Phase I utilizing cm-scale EnMats</li> <li>Fabricate, integrate, and test optical systems utilizing large cm-scale conformal and non-conformal EnMats</li> </ul>
TA2: Multifunctional Optics	<ul style="list-style-type: none"> <li>Develop theories and concepts for multifunctional EnMats</li> <li>Explore limits and tradeoffs of multiplexing functions (static and dynamic)</li> <li>Propose architectures utilizing EnMats for multifunctionality</li> </ul>	<ul style="list-style-type: none"> <li>Design and optimize system concepts from Phase I utilizing cm-scale multifunctional EnMats</li> <li>Fabricate, integrate, and test optical systems utilizing cm-scale multi-functional EnMats</li> </ul>
TA3 (a & b): Modeling, Design & Optimization	<ul style="list-style-type: none"> <li>Develop multiscale modeling and simulation of EnMats from nm to cm scale</li> <li>Design and optimize EnMat-based optical system</li> <li>Establish the relationship between EnMat building blocks and bulk scale performance and v.v.</li> </ul>	<ul style="list-style-type: none"> <li>Utilize multiscale models to design and optimize cm-scale EnMat-based optical systems with TA1 and TA2 teams</li> <li>Design new EnMat building blocks based on taxonomy developed in Phase I</li> </ul>



## KEY ELEMENTS OF BAA

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# Thoughts on prior art

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BAA Excerpt: "Please note that DARPA is interested in the application of EnMats to novel optical architectures, and not on advancing any specific EnMat during this program. Specifically not of interest to EXTREME is conventional gradient refractive index (GRIN) optics."

## **In the context of the prior art, DARPA EXTREME is:**

### **Interested in, but not limited to:**

- EnMats - metamaterials (both metallic and dielectric), scattering surfaces and volumes, holographic structures, and diffractive elements.
- EnMat surfaces and volumes are both acceptable, and are not mutually exclusive; volumes represent a frontier problem with tremendous potential!
- Operation in VIS/NIR is of primary interest; less interested in SWIR, MWIR and LWIR
- Reconfigurable/dynamic operation

### **Not interested in:**

- Classical Gradient Index materials and optical components
- Marginal material advancements without associated dramatic advancements in optical performance
- Evolutionary advancements in volume holograms and/or diffractive optics
- RF/THz operation



# What Constitutes (high-level) Success in Each Phase?

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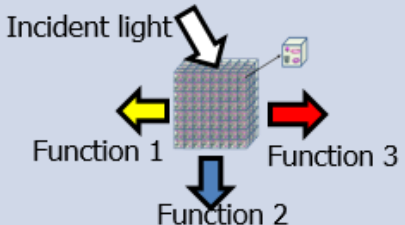
BAA Excerpt: “EXTREME is divided into two 24-month phases. Proposals must address both phases and should be structured with Phase I tasks/costs as the base effort and Phase II tasks/costs as an option. Phase I focuses on exploration and verification of newly designed EnMats with expanded capabilities on a small spatial scale. Phase I also includes the development of new multiscale modeling, simulation, and optimization tools. The goal of Phase I is to advance theoretical understanding and enhance the capabilities of EnMats so they can be used in practical optical systems. The goal of Phase II is to utilize Phase I concepts to design, fabricate, and demonstrate EnMat-based optical systems and architectures on a large spatial scale (each spatial dimension must be  $>1$  cm). Additionally, Phase II work will continue to refine modeling and design environments.”

- Success in Phase I has many dimensions:
  - Demonstrate EnMats with new or greatly improved performance/capabilities (size of components is not important)
  - Understand fundamental limits, accurately model the fundamental physics, implement the EnMat in an optical design environment
  - Simulate potential performance in a novel optical architecture
  - Develop a feasible plan to scale size of EnMats (ideally through initial experiments)
- Phase II success is measured by an experimental demonstration of EnMat based optical system on a cm scale.



# Functionality Examples

**BAA Excerpt:** “As an example, for the purposes of this solicitation, an imager is considered to perform a single function, a spectrometer is considered to perform a single function, a hyperspectral imager would be considered to perform two functions, and a compressive hyperspectral imager would be considered to perform three functions. DARPA is interested in multifunctional element(s) which could potentially replace an entire SOA system.”

Device	Functions
Imaging system	1. Intensity imaging
Spectrometer	1. Spectral separation
Pulse shaping	1. Spectral shaping
Hyperspectral imaging	1. Intensity imaging 2. Spectral separation
Light field imaging	1. Intensity imaging 2. Incident angle
Light field multispectral imagers	1. Intensity imaging 2. Spectral separation 3. Incident angle
“Sugar cube” 	1. Intensity imaging 2. Spectral separation 3. Polarization measurement 4. ....



# Teaming

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**BAA Excerpt:** “Therefore, all proposals must discuss not only initial partnerships and teaming arrangements but also discuss mechanisms and structures for formally sharing information, data, technical knowledge, expertise, and other resources to facilitate collaboration. Proposals must also discuss intellectual property (IP) arrangements and any potential barriers to collaboration. IP is discussed in further detail below and in Section VI.B.1. Proposals should clearly indicate whether software tools being developed will be made available to other EXTREME performers and/or to the community at large, and provide an expected timeline for information sharing.”

**New optical architectures are the driving force of the EXTREME program, and we believe that it will take a community effort to develop the requisite tools to realize these designs. This can only occur if:**

- Groups proposing to TA1/TA2 should note that they must include sufficient modeling, design, and optimization capabilities to accomplish their TA1/TA2 goals.
- TA1/TA2 efforts should share data and results at least with TA3-only efforts, and preferably with other TA1/TA2 teams.
- All TA3 efforts should provide expertise to TA1/TA2 teams.



## **TA1/TA2/TA3**

- Proposers may apply to any and all TAs.

## **TA1 and/or TA2 only**

- If applying to TA1 and/or TA2, proposers must provide their own modeling, design, and optimization capabilities to accomplish their TA1 and TA2 goals, but these capabilities can be narrowly focused on the proposed EnMats. By “focus” we mean that it is acceptable to work on modeling, optimization and optical design for your specific EnMat(s) **only**.
- Note: These capabilities can be based on already developed modeling tools and approaches. This work may not require the solicitation of expertise outside of your TA1/TA2 team.
- However, from DARPA’s point of view it is desirable that teams that propose focused TA1 and/or TA2 efforts also work with individual proposers to TA3 (a&b) in the program.

## **TA3(a) and/or TA3(b)**

- If applying solely to TA3(a/b), developed tools and subject matter expertise will be provided to all TA1 & TA2 teams and v.v.



# Challenge Problem: detailed description

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## Challenge Problem:

*“Demonstrate (design, build, and test) an optical system architecture relevant to the DoD that achieves at least an order of magnitude SWaP reduction and/or revolutionary performance improvement over equivalent SOA system. The proposed architecture must utilize at least one EnMat component that either modifies the conventional laws of light propagation, or operates as a multifunctional optical element, or both.”*

- Example challenge problems are provided in the BAA and on the next slide, but for illustrative purposes only.
- Proposers do not have to address any specific challenge problem from the example list, and are free to submit their own challenge problem.
- All proposals must address the challenge problem with the exception of proposals to TA3(a) only.

**DARPA re-emphasizes that the challenge problem is intended to develop new optical system architectures based on EnMats, and that EnMat development not specifically tied to and motivated by new architectures is not of interest to the EXTREME program.**





# “DoD Relevance”

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## BAA Excerpt:

- A non-vignetting  $\geq 2\pi$  steradian F/1 imager composed of reflective, catadioptric, and refractive with any number of EnMat components
  - A single volume “sugar cube” which performs several different functions in the same volume
  - Night vision goggles with the form factor of eye glasses
  - Wavefront shaping: flat interfaces for arbitrary light bending and curved interfaces for no bending (e.g., aberrationless domes, etc.)
  - Zero optical signature: surfaces for dynamic camouflaging (adaptive redistribution of light flow, total absorption/transmission, etc.)
  - Light Beam and/or imager FOV steering over  $2\pi$ , and other active systems without moving elements
  - Task/feature specific optical systems that incorporate the majority of the “computation/processing” into the optical system
  - A 4  $\pi$  steradian extremely fast imager based on a true Luneburg lens
- This list is generic. It is not DoD system specific. It is neither exhaustive nor binding in any way.*
- This is the level of association of DoD value to your proposed solutions that we are looking for.
  - All of these examples are DoD relevant without being tied to a specific DoD system or application.
  - Improving on a currently fielded system doesn't carry any extra weight over these more general examples.



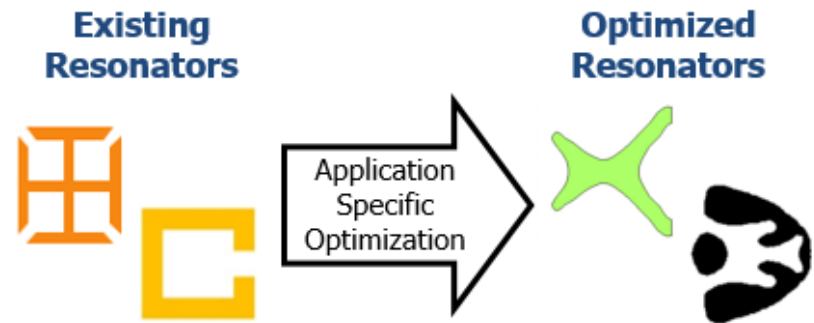
# The Role of TA3-only Proposals

## Expected Outcomes for TA3(a) Multiscale Modeling and Simulation:

- Multiscale modeling tools that potentially operate over 7 orders of magnitude of spatial scale
- Forward and inverse models for EnMat components, systems, and architectures
- Ability to derive and/or optimize new shapes and geometries for the building blocks of EnMats

**“Periodic Table” to derive  
and design resonators**

MM Sub	n=1			n=2		
	pm	pmm	p4m	cm	cmm	p4m



## Expected Outcomes for TA3(b) Optical System Design and Optimization:

- Design of optical systems which utilize large spatial scale EnMat components
- Development of design principles (e.g., heuristics and rules of thumb) to guide the incorporation EnMats into conventional optical systems
- Design and optimization environments constructed around EnMats in order to achieve next generation optical architectures



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